

## Enhancement of the Performance of Vector Controlled Back-to-Back VSC System under Grid Disturbances

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### Abstract

The increasing emergence of VSC-based transmission is the result of development in semiconductor devices, power electronic circuits, control, and executive engineering. The most important limiting factor of power semiconductors is their switching properties since they are usually optimized for the conduction intervals. This concept specifically proposes a control structure to improve the performance of high-power vector-controlled back-to-back VSC systems for wind generators and for transmission systems applications. The main improvement is to suppress the possible dc-link voltage fluctuations under power line faults and unbalanced conditions. The proposed controller structure is designed based on regulating the converter system's states locally in  $d-q$  synchronous reference frame without sequence components extraction or resonant notch compensator. The mat lab results verify the validity of the proposed control architecture during normal and unbalanced power system conditions.

**Index terms:** Vector controlled, VSC, Wind, Recovery transformer, Matlab

### I. Introduction

It is desirable to have high-power high-voltage converter based systems available during power system faults when they may be needed the most. Voltage-source converter (VSC)-based transmission systems have attractive potential features in terms of power flow control and stability of the network. A voltage-source converter (VSC) is the main building block for flexible ac transmission systems (FACTS) devices and, as of today HVDC technology up to several hundred megawatts. Although relatively low switching frequency operation of high-power converters (9–15 times the line frequency) is desirable, it makes them sensitive to power network imbalances when they may be needed the most.

Today, the most promising market for HVDC technology is interconnection of the networks where the centers of the loads are located far from the points of connection. The problem of ac systems arises as the phase angle drifts and varies over a wide range with daily load changes [3].

This phenomenon especially in a weak ac network along with the power line faults exacerbates the operation of HVDC systems. If the protection measures trip the converter system, it can take several fractions of an hour, depending on the size of the converter, to discharge the dc link and check the healthiness of the whole system. Hence, several practical methods have been proposed and implemented to keep a system operating under power system faults and disturbances [1], [2]. However, generally, less dependence on power semiconductor characteristics amounts to having more supplier possibilities for the VSC-based transmission.

The most important limiting factor of power semiconductors is their switching properties since they are usually optimized for the conduction intervals. Hence, high-power electronic converters are desired to operate with relatively low switching frequencies (maximum 9–15 times the line frequency, and even lower for multilevel converters). The low switching frequency operation of VSC systems imposes control limitations in case of power system faults and disturbances when they may be needed the most. This paper specifically proposes a control structure to improve the performance of high-power vector-controlled back-to-back VSC systems for conventional and emerging utility applications.

The main improvement is to suppress the possible dc-link voltage fluctuations under power line faults and unbalanced conditions. The increasing emergence of VSC-based transmission is the result of development in semiconductor devices, power electronic circuits, control, and executive engineering, [4]–[6]. Previously, the lack of these developments had prohibited the VSC-based technology from being the first choice. While each development is moving forward individually, the result of each one influences the design criteria and application requirements of the overall system. To the best of the authors' knowledge with emerging high-power applications such as 10-MW wind generation turbines or transportable recovery transformers, the dynamic operation of the VSC under power system disturbances must be revisited.

This paper proposes an alternative control framework to obtain robust dc-link voltage with specific attention to design the VSC controller in the back-to-back (BTB) configuration. The proposed controller is implemented in the  $d-q$  (rotating)

synchronous reference frame without sequence extraction system.

The proposed controller structure is designed based on regulating the converter system's states locally in d-q synchronous reference frame without sequence components extraction or resonant notch compensator.

## II. Modeling of VSC

The modeling of VSC, the building block of the BTB system, is based on the state-space average modeling approach. This modeling is based on the principal circuit analysis and voltage and current equations for storage elements known as state equations. the state equations of a VSC in the three-phase stationary coordinates are as follows:

$$\frac{dI_{abc}}{dt} = -\frac{R_s}{L_s}I_{abc} + \frac{E_{abc}}{L_s} - \frac{V_{abc}}{L_s} \quad (1)$$

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} - \frac{V_{DC}}{R_p C_{DC}} - \frac{P_{load}}{C_{DC} V_{DC}} \quad (2)$$

In order to benefit from all decoupling and constant properties of a two-phase system instead of a three-phase one, d-q transformation is considered to convert all quantities in the abc stationary coordinate frame to the synchronously rotating reference frame, i.e., de-*q*e

$$\frac{dI_d}{dt} = -\frac{R_s}{L_s}I_d - \omega_s I_q + \frac{E_d}{L_s} - \frac{V_d}{L_s} \quad (3)$$

$$\frac{dI_q}{dt} = -\frac{R_s}{L_s}I_q + \omega_s I_d + \frac{E_q}{L_s} - \frac{V_q}{L_s} \quad (4)$$

In (3) and (4),  $V_d$  and  $V_q$  are the converter output voltages in the synchronous reference frame. The modulation index can also be written in this frame as (5) where  $k$  depends on the modulation technique. In this study, we use the vector control method or type-I control

$$m_d = \frac{V_d}{kV_{DC}}, \quad m_q = \frac{V_q}{kV_{DC}} \quad (5)$$

In many literature works especially for dc/dc converters, the modulation index is used as the control input; therefore, (3) and (4) present the nonlinear system. DC-link dynamics are also nonlinear by introducing the definition for  $I_{DC}$  as (6). However, by considering  $V_d$  and  $V_q$  as the control inputs, (3) and (4) can be treated as linear ones. Also, power balance is used to derive the equation for the dc-link voltage neglecting the interface losses as in (7).  $E_a$  (the PCC phase A voltage) is aligned with the  $d$ -axis in the synchronously rotating reference frame.

The result of dc-link dynamics shown in (7) is linear as long as  $E_d$  and  $E_q$  are constant. Consequently, no linearization around specific operating points is needed and the small-signal VSC

model looks similar to the large-signal model. The state-space representation of the VSC can be obtained from (3), (4), and (7). State variable vector  $x(t)$  is the state variable vector,  $u(t)$  is the input vector, and  $e(t)$  is considered as the disturbance vector, (8)

$$I_{DC} = \frac{3}{2}(m_d I_d + m_q I_q) \quad (6)$$

$$\frac{dV_{DC}^2}{dt} = \frac{3E_d I_d}{C_{DC}} + \frac{3E_q I_q}{C_{DC}} - \frac{2V_{DC}^2}{R_p C_{DC}} - \frac{2P_{load}}{C_{DC}} \quad (7)$$

$$x(t) = \begin{pmatrix} I_d \\ I_q \\ V_{DC}^2 \end{pmatrix}, \quad u(t) = \begin{pmatrix} V_d \\ V_q \end{pmatrix}, \quad e(t) = \begin{pmatrix} E_d \\ E_q \\ P_{load} \end{pmatrix} \quad (8)$$

In the vector-controlled BTB VSC systems regardless of the topology, one converter typically controls the dc-link voltage and supports its reactive power. This converter can be operated as rectifier in HVDC applications or as an inverter in direct driven wind turbines. The other converter is operated in  $PQ$  or  $V/f$  (voltage/frequency) mode controlling the active and reactive powers. A simplified schematic of the BTB VSC system with its control. To design a closed-loop system, the eigen structure assignment or any linear feedback design method can be used to place the poles at the desired locations. Eigen structure assignment is explained for STATCOM and we use it to develop the general controller and as the baseline for the VSC in the BTB configuration as presented. According to the system equations, the mode associated with the  $q$ -component of the current (typically for reactive power control) can be adjusted based on the ac-side interface parameters and required response time.

On the other hand, dc-link voltage closed-loop dynamics consist of the modes associated with two eigen values. One of the system poles affects the charging and discharging of the capacitor which is called  $\lambda_c$ . This eigen value should be placed near to the origin to avoid either high charging or discharging current. The other pole can be placed at the same location the reactive current control mode is, which we call it  $\lambda_i$ . It should be noted that the poles associated with the current mode can be placed as far as the inherent delay of the converter modeling allows; current regulators often present a fast first order behavior. To achieve a non oscillatory output response, it is sufficient to place the poles at the real axis. Consequently, the dc-link voltage regulator can be designed based on the system specifications and requirements. The performance of the BTB system under balanced conditions through the proposed modeling and control.

## III. BTB VSC System for Drive (Wind) Applications

This section is provided to address emerging large capacity wind turbines (>10 MW). These turbines are expected to use direct-drive technologies

shown in Fig.1 and the BTB VSC system as the enabling interface. A robust dc-link voltage is considered to be one of the key factors that affect the turbine operation. In the following case studies, it is assumed that the turbine-side converter (VSC 2) operates at 30 Hz and supplies 0.8 p.u. active power and absorbs 0.6 p.u. inductive reactive power, while the grid-side converter (VSC 1) regulates the dclink voltage and provides 0.2 p.u. capacitive reactive power. The dynamic performance of the VSC BTB system in the drive application under unbalanced conditions in the inverter side or grid side (dc-link voltage controller converter) is presented in Figs .1,2, 3, 4. In Fig. 1, the unbalance system is represented by 50% voltage drop in phase B of the inverter-side PCC. In Fig.5,6,7,8, a more severe fault occurs which is represented by a 50% voltage sag in phase B in addition to a 30% voltage drop in phase C of the grid. From the results obtained, it can be concluded that the proposed control scheme is effective in maintaining a robust dc-link voltage even under unbalanced grid conditions. In other words, the drive side in this case of high power wind generators with a BTB VSC interface can operate independently from the grid disturbances translating to higher availability of the renewable resources.

**4. BTB VSC System for Transmission Transformer (Partial) Bypass**

With increasing demands of power electronics in the network, it is expected to have hybrid systems. One example of a hybrid system approach is known as the modular transformer converter (MTC) in which a single or a group of BTB

VSC system(s) is connected across transmission-level transformers. An MTC as the transmission controller provides the flexibility of full or partial utilization for the transmission lines and power transformers. This flexibility effectively increases the system’s spare capacity and operating margins, and also provides back-up in case of substation transformer failure or forced reduced rating operation scenarios by continuous power flow control. A simplified schematic of the MTC as the transmission controller connected in parallel to a transmission transformer is depicted in Fig.12. Introducing the MTC, as shown in Fig. 9,10,11, brings remarkable effects on the dynamics of the system. In particular, any imbalance in the power system is seen by both converters, which has been little appreciated in conventional applications of BTB VSC systems.

The dynamic performance of the VSC BTB system with the proposed control structure for hybrid power system applications under balanced and unbalanced conditions is presented in Fig.9,10,11. The power flow in the BTB system remains as stated in the previous case studies except that the two networks have a 5° phase difference for the natural power flow of the grid. The unbalanced system is represented by a 90% voltage drop in phase A of the PCC voltages. As can be observed, the dc-link voltage remains practically stiff, and harmonic measurement of the dc-link voltage for the second and fourth harmonics shows a satisfactory level of compensation under this severe fault case. Therefore, an MTC with the proposed control structure can be utilized even under unbalanced conditions when it is needed the most.

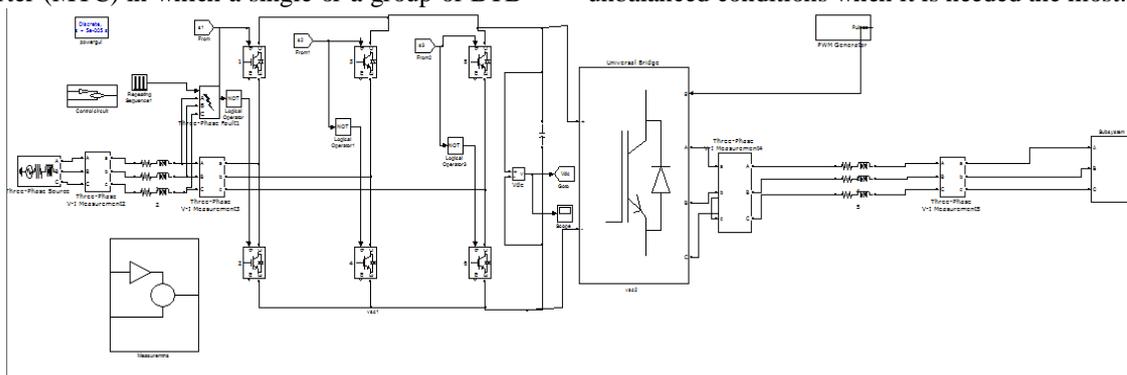


Fig.1. Simulink model for the proposed circuit(Wind application)

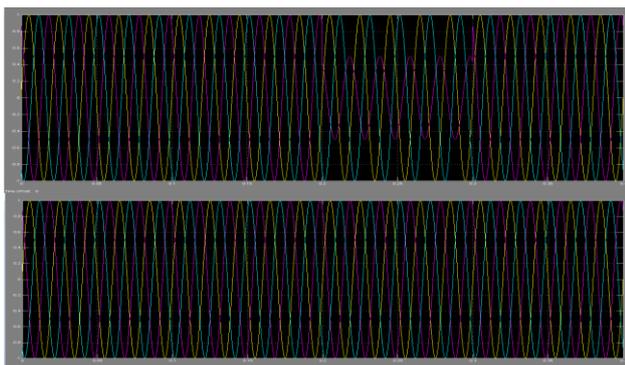


Fig.2. Output Voltages of Vsc1, Vsc2.

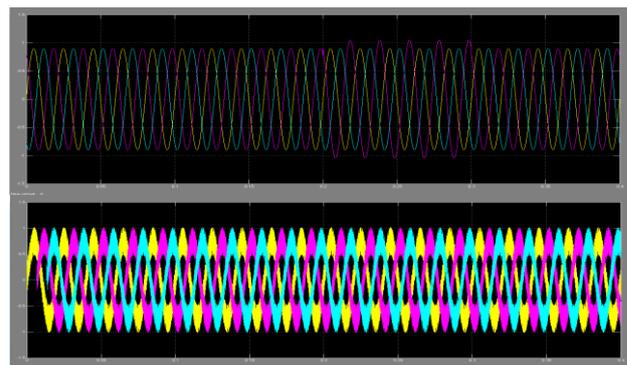


Fig.3. Output currents of Vsc1, Vsc2.

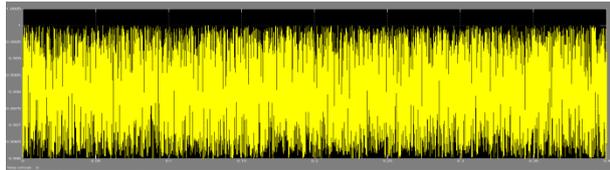


Fig.4.DC link voltage.

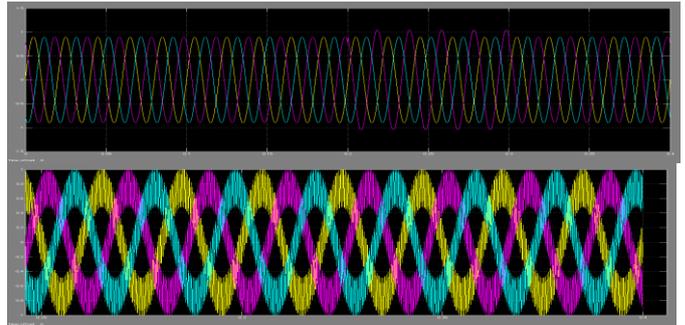


Fig.6.Output currents of Vsc1,Vsc2.

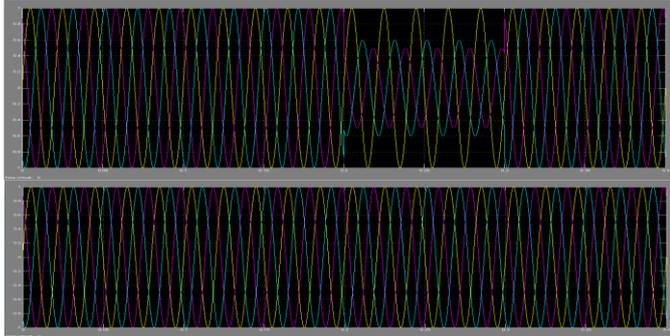


Fig.5. Output Voltages of Vsc1,Vsc2.

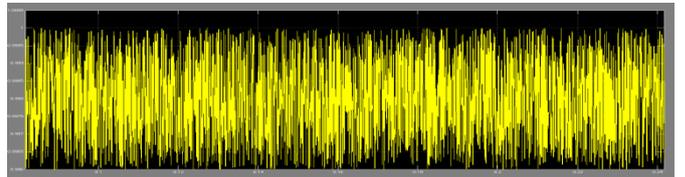


Fig.7.DC link voltage.

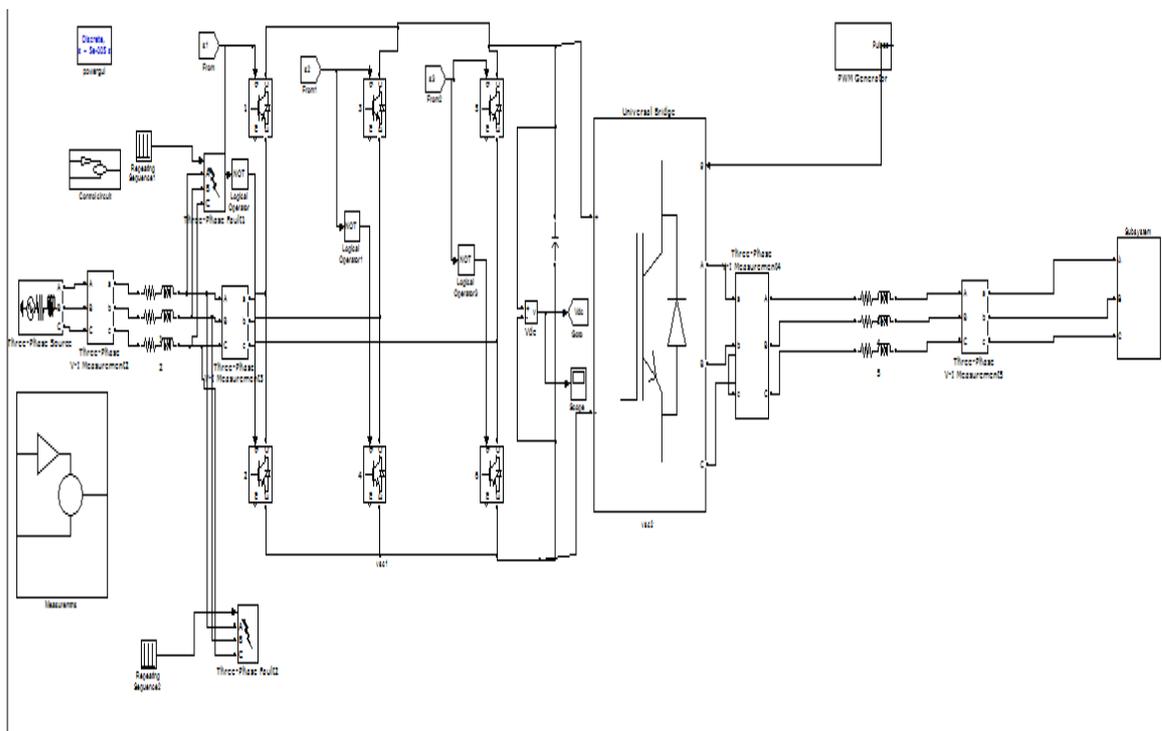


Fig.8.Simulink model of proposed circuit under faults at phase B,C .

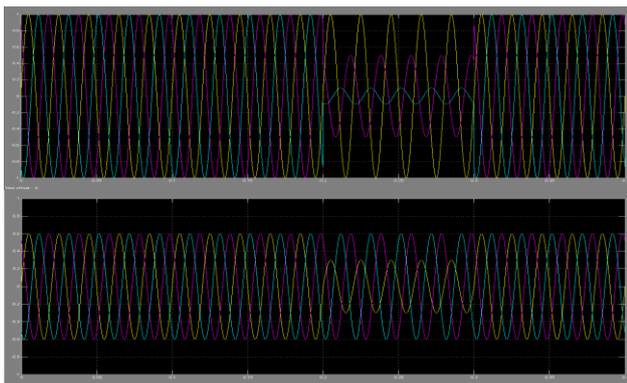


Fig.9.Output voltages of Vsc1,Vsc2.

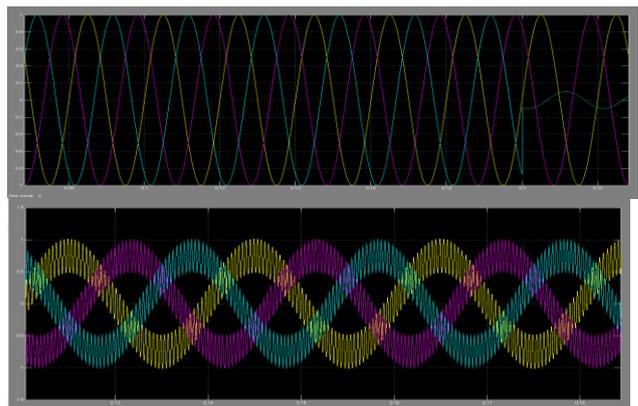


Fig.10.Output currents of Vsc1,Vsc2.

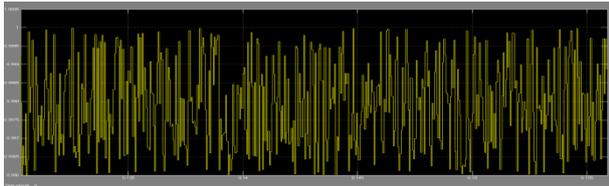


Fig.11. DC link voltage.

#### IV. Conclusion

This paper has addressed the dc-link voltage control issues for vector-controlled VSC-based transmission systems under power system disturbances. Having analyzed the current state-of-the-art methods of mitigating the dc-link voltage fluctuations under grid faults and disturbances, we have proposed a control structure in the commonly used d-q synchronous reference frame. The proposed

structure obviates the need for the sequence extraction blocks or the resonant compensators. Therefore, there is no diminishing bandwidth factor.

The scheme, however, utilizes the interaction of the converters, the load, bus voltage, and their derivatives to compensate for the phase delay in the current regulator. The proposed scheme was explained through a back stepping control method in which its Lyapunov-based structure ensures the stability of the system. The RTDS verification of the controller attained less than 1% dc-link voltage deviation under most common faults and disturbances, demonstrating the applicability and effectiveness of the proposed scheme for different transmission applications denoted as HVDC, drive, and hybrid power systems.

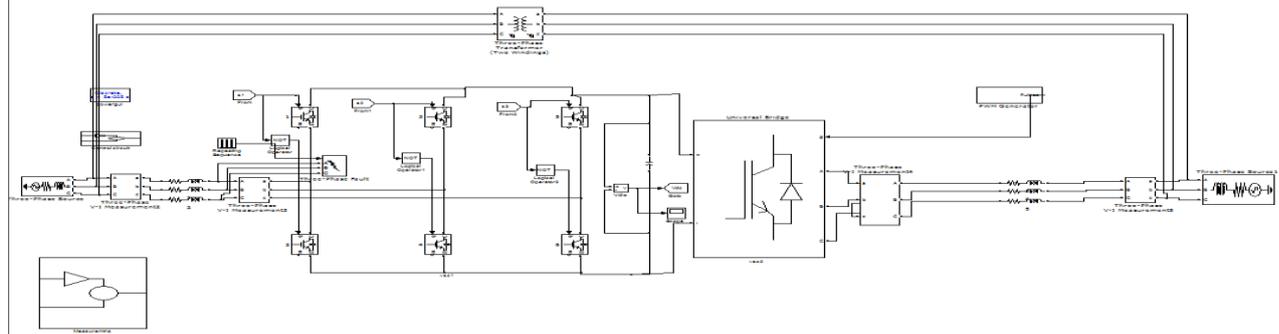


Fig.12. Simulink model of proposed circuit for transformer application

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